# Silicon-on-Insulator First-Order Mode Converter Based on Binary Phase Plate


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***Abstract*—A silicon-on-insulator fundamental to first-order mode converter is proposed based on binary phase plate. The device can be operated in both polarizations simultaneously as it converts both fundamental $TE_0$ and $TM_0$ modes to first-order $TE_1$ and $TM_1$ modes, respectively which will be very useful in implementing PDM-MDM systems. The proposed device has a simple and compact structure. It has a low insertion loss of -2 dB and low crosstalk.**

***Index Terms*—silicon photonics, mode converter, phase plate, waveguide**


## I. Introduction

Silicon photonics is a promising technology for providing faster data rate and maximizing the transmission capacity in order to keep up with the demands in the traffic growth. Increasing capacity requires the multiplexing techniques to be demonstrated in silicon-on-insulator (SOI) platform. Mode-division multiplexing (MDM) and space-division multiplexing (SDM) techniques are enabling technologies for increasing capacity [1], [2]. Normally these techniques require mode conversions from fundamental modes to specified higher-order modes before multiplexing into a multimode waveguide. One of the most commonly used methods for mode conversion is based on the use of phase plates due to its simplicity and good selectivity conversion at the design wavelength [3]–[5]. The propagating modes in silicon waveguide are orthogonal to each other. Thus, to selectively excite one specific mode, it is sufficient to match the phase profile of that particular mode. This can be achieved through phase modulation of the input field By placing a proper phase element in its path [6].

Tilted binary phase plates have been investigated in optical communications systems for dynamic and efficient mode conversion not only for the design wavelength but also over a wide spectral range [7]. Phase plates which phase patterns match that of higher-order modes are made of glass with thicker part of its surface. This introduces a phase jump of $\pi$ to light that passes through it. A phase plate has many phase pattern shapes for different higher-order modes [4]. According to the specified higher order mode, a phase pattern will be picked up.

In this paper, a simple phase plate mode converter is proposed in silicon-on-insulator. The device converts a fundamental $TE_0$ ($TM_0$) mode in a silicon waveguide to first-order $TE_1$ ($TM_1$) mode with a good conversion efficiency and low crosstalk at $1550\,\mathrm{nm}$ wavelength. The structure is composed of a phase plate converter sandwiched between an input and output multimode waveguides. The dimension of phase plate converter is about $5.48\,\mu\mathrm{m}$ length and $2.5\,\mu\mathrm{m}$ width.

## II. Proposed System Model

The proposed structure is schematically illustrated in Fig. 1a. The device consists of a silicon input multimode waveguide, a silicon output multimode waveguide, and a first-order silica phase plate mode converter on the top of a $SiO_2$ box layer with air cladding.

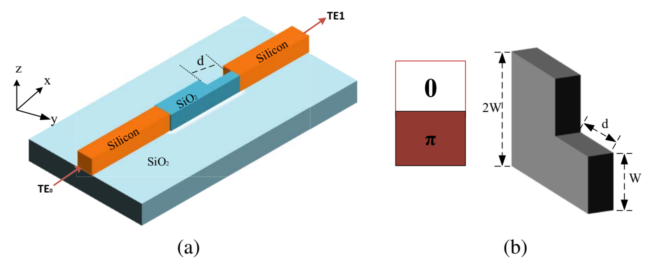


Fig. 1: (a) Schematic diagram of proposed structure, (b) Phase pattern of first-order mode with cross-sectional area of phase plate.

For fundamental to first-order mode converter, a phase pattern of first-order mode is used as shown in Fig. 1b. This phase coupling element introduces a phase profile identical to that of the first order mode at the facet of the output waveguide. The transfer function of this phase element can be represented by a sign function as in 1. The slab waveguides in the proposed device are pointed in *y* direction so the transmittance function of the phase plate affects the fundamental mode in *y* direction only. The center point of both the input and output waveguides and phase mask is the same and is located at $y = 0$. After applying the transmittance function of phase plate on the fundamental mode at the facet of the output waveguide , the phase distributions of the resultant field matches that of the first order mode. For the amplitude distributions of the resultant field to be similar as the amplitude of first order mode, the dimensions of the phase mask must be designed

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according to the input and output waveguides dimensions to increase the coupling efficiency to the first order mode.

$$T(y) = sign(y) = \begin{cases} 1 & \text{if } y > 0 \\ 0 & \text{if } y = 0 \\ -1 & \text{if } y < 0 \end{cases} \quad (1)$$

The pattern of silica phase plate is composed of two parts. One of them is thicker by a distance of $d$ and the phase pattern thickness $d$ is the design parameter to convert light from fundamental to higher-order mode at a specific wavelength. The width of this thicker part must be at a half-width of the other part. Through the thicker part of phase plate, the incident light would experience a phase shift of $\pi$ relative to the other part of phase plate. This is because the light is propagating in two different media with different refractive indices. The distance $d$ is calculated at specific wavelength by the following equation:

$$d = \frac{\lambda}{2\,(n_1 - n_2)}, \quad (2)$$

where $n_1$ and $n_2$ are the refractive indices of the phase plate and the cladding, respectively. The accumulated light at the output waveguide after phase plate is the first-order mode. For converting the fundamental mode to other higher-order mode, the phase pattern must be altered and the binary phase plate should be redesigned in accordance with the new pattern.

## III. FDTD Simulations and Results

In this section, we present 2D-FDTD simulation of proposed device. A fundamental TE mode is launched to the input waveguide at $1550\,\text{nm}$ wavelength. The design parameter $d$ is determined from (2): $d = 1.48\,\mu\text{m}$. The refractive index of phase plate is $n_1 = 1.44$ and $n_{silicon} = 3.477$ with air cladding. The rest of our design parameters are chosen based on sweeping every parameter to get the best performance. The width of the first part of phase plate is $2.5\,\mu\text{m}$, which is equal the width of the output waveguide. The width of the second part of phase plate is half that of the first part, while the width of the input waveguide is $2\,\mu\text{m}$.

The length of the first part of phase plate is $4\,\mu\text{m}$ and the proposed structure height is $220\,\text{nm}$. Figure 2 shows that $TE_0$ to $TE_1$ mode conversion is achieved with insertion loss of $-2\,\text{dB}$ and a minimum crosstalk of $-25\,\text{dB}$ to both $TE_2$ and $TE_4$ modes and low crosstalk of about $-20\,\text{dB}$ and $-10\,\text{dB}$ to both $TE_3$ and fundamental $TE_0$ modes, respectively.

Furthermore, the proposed device can also convert fundamental $TM_0$ to $TM_1$ by just launching a fundamental $TM_0$ at the input waveguide. Figure 3 shows the insertion loss is about $-2.5\,\text{dB}$ and crosstalk to both $TM_4$ mode and $TM_2$ mode is about $-15\,\text{dB}$ while the crosstalk is $-16\,\text{dB}$ and $-8\,\text{dB}$ to $TM_3$ mode and fundamental $TM_0$ mode, respectively. Placing a phase element in the light propagation path does not cause power loss in silicon-on-insulator platform. As shown in Figs. 2 and 3, the total power received in output waveguide doesn't influence with the mode conversion process .

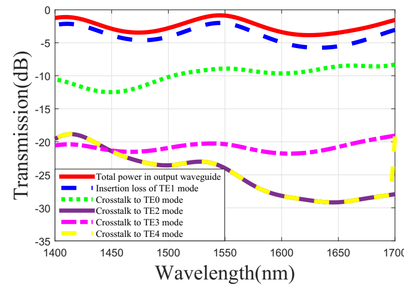


Fig. 2: Insertion loss for $TE_1$ mode conversion

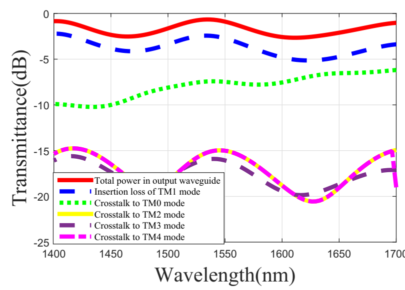


Fig. 3: Insertion loss for $TM_1$ mode conversion

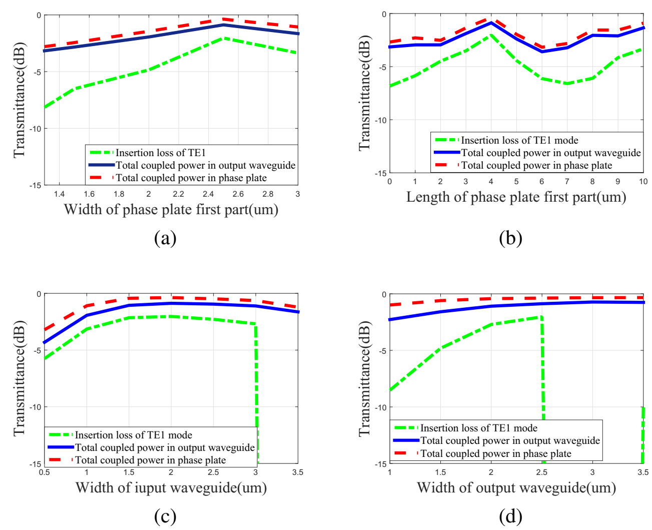


Fig. 4: FDTD simulation sweep for design parameters: (a) sweep for width of first part of phase plate, (b) sweep for length of first part phase plate, (c) sweep for width of input waveguide, and (d) sweep for width of output waveguide.

Figure 4 shows the influence of other design parameters on the success of mode conversion process. Figures 4 (a,c,d) indicate that the maximum insertion loss for $TE_1$ mode can be realized when the width of first part of phase plate equals the width of both input and output waveguides. That is, in the proposed design the width for all components is around

$2.5\,\mu m$. This is consistent with the fact that if the dimension of phase plate approaches the dimensions of input and output waveguides, coupling efficiency increases.

When the width of input and output waveguides is larger than the phase plate width, the mode conversion process misses due to the mismatch between the mode field diameters in the waveguide and phase plate. The length of the first part of phase plate affects the insertion loss of $TE_1$ as shown in Fig. 4(b). From the sweep, the maximum insertion loss is achieved at $4\,\mu m$ for previously chosen parameters. It is worth noticing from the figures that changing the other design parameters do not impact the transmission of the total power, rather they affect the mode conversion process.

## IV. CONCLUSION

Silicon on insulator $TE_0$ to $TE_1$ mode converter has been proposed. The mode converter structure is based on binary phase plate. It has the advantage of being compact; its length is $5.48\,\mu m$ and its width is $2.5\,\mu m$ with the input and output waveguides inserted. In addition, an insertion loss of $-2\,dB$ have been achieved for first-order mode conversion.

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